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Implications of NiMH Hysteresis on HEV Battery Testing and Performance

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Abstract

Nickel Metal-Hydride (NiMH) is an advanced high-power battery technology that is presently employed in Hybrid Electric Vehicles (HEVs) and is one of several technologies undergoing continuing research and development by FreedomCAR. Unlike some other HEV battery technologies, NiMH exhibits a strong hysteresis effect upon charge and discharge. This hysteresis has a profound impact on the ability to monitor state-of-charge and battery performance. Researchers at the Idaho National Engineering and Environmental Laboratory (INEEL) have been investigating the implications of NiMH hysteresis on HEV battery testing and performance. Experimental results, insights, and recommendations are presented.

Keywords: HEV, battery, nickel metal hydride, hysteresis, and state of charge

1. Introduction

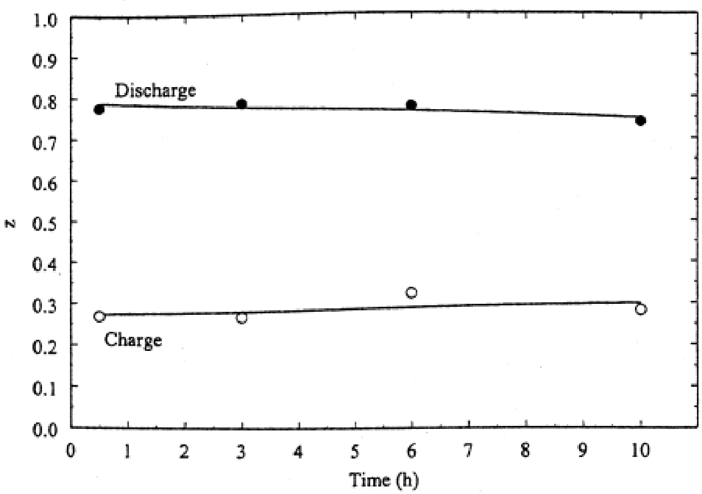
In 1993, the U.S. Department of Energy (DOE) and the U.S. Council for Automotive Research (USCAR) formed the Partnership for a New Generation of Vehicles (PNGV) to develop Hybrid Electric Vehicles (HEVs) with fuel economies up to 80 miles per gallon, while simultaneously maintaining other performance and cost parameters. PNGV was superceded in January 2002 by FreedomCAR, whose emphasis is the development of fuel cell powered vehicles.

In support of the FreedomCAR program, the INEEL has initiated studies on advanced high-power NiMH battery modules and cells to develop standardized tests for assessing their performance against FreedomCAR's 15-year calendar-life goal. Previous calendar life testing used a combination of voltage-clamped storage (at various temperatures) and periodic reference tests that fully charge and discharge a battery. The FreedomCAR technical team determined that future testing might require testing at open-circuit conditions, in some cases without the ability to do full charges and discharges for reference performance measurements.

Unlike other high-power batteries such as Lithium-Ion, NiMH batteries exhibit a strong voltaic hysteresis between charge and discharge. Hysteresis has a profound impact on the ability to monitor and control state-of-charge (SOC) and measure battery performance. As a consequence, previously developed calendar life-tests may not be applicable to this technology and no easy method (short of completely discharging the battery and measuring its residual capacity) presently exists for determining the energy remaining in the battery during use.

Srinivasan et al. state that two oxidation states [i.e., SOCs] can exist at the same potential depending only on the previous history of the electrode. Consequently, the potential of nickel-based batteries cannot be used as an indication of the SOC of the cell. This is depicted in Figure 1 [1], which shows the SOC, (z on the y-axis) as a function of time for two identical electrodes clamped to the same voltage after starting from a fully charged state and from a fully discharged state. Although each electrode is at the same clamp voltage, the SOCs are clearly different.

This problem is further shown in Figure 2. The figure shows the $C_1/25$ discharge and charge curves for a representative NiMH battery module. This test was run once with one-hour rests at open circuit voltage (OCV) at the top and bottom of charge, and repeated once without the one-hour rests to determine the impact of rest intervals on SOC measurements. Results in both cases are very similar. However, the dashed lines in the figure illustrates that for a given voltage the corresponding SOC can



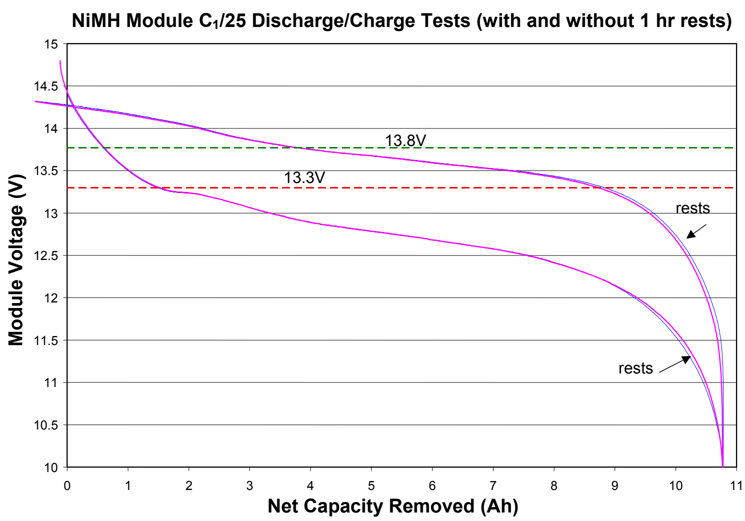


Figure 2. NiMH C/25charge and discharge curves.

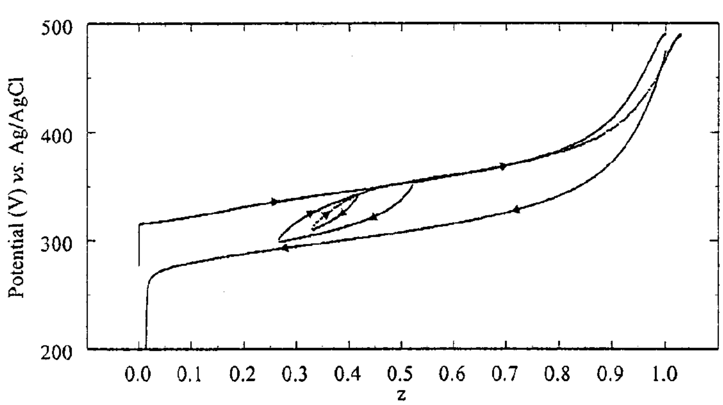


Figure 3. Effect of previous charge history on voltage [1].

cover a wide range (e.g., the 70% SOC OCV of 13.3V spans about 7 Ah or greater than 60% of the SOC range.)

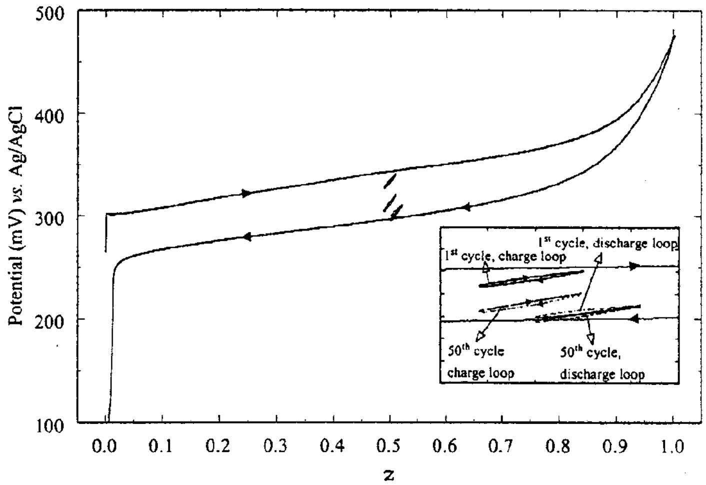
Also, Srinivasan et al. reported that it is possible to reach any voltage/SOC state between the charge and discharge curves from an infinite number of starting states. As shown in Figure 3 [1] the direction the voltage/SOC state will move next depends on the history of how it was reached. Also, each hysteresis loop wipes out the history of previous excursions. Further, we have observed that while holding the battery at a fixed voltage, the SOC slowly drifted from the discharge curve toward the charge curve. So, any control scheme that relies on voltage alone can potentially be very inaccurate.

Lastly, during small, closed-loop cycling around a target voltage, the SOC of the system slowly drifted from the charge curve to the discharge curve as shown in Figure 4 [1], i.e., the hysteresis effect is not perfectly preserved.

Preliminary results have identified a number of critical factors for controlling NiMH calendar-life testing at the desired target conditions, including its previous history, charge/discharge direction, and voltage control.

2. Hysteresis Studies

With the hysteresis issues described above in mind, INEEL began a series of experimental studies on two different sets of NiMH batteries. The first set was developmental 11-Ah NiMH modules previously provided to INEEL by Texaco Ovonics Battery Systems (TOBS) for evaluation under the PNGV program. The second set was commercially available 0.65-Ah NiMH single cells manufactured in China. Two TOBS modules and 16 of the smaller NiMH single cells were tested. Tests were duplicated on more than one battery to eliminate questionable results originating from non-uniform test articles. All testing was performed at 25°C in environmental chambers to minimize effects due to temperature fluctuations and all tests were conducted using programmable MACCOR Corporation testers.



4. SOC drift during small closed-loop cycling [1].

Numerous tests were performed on the cells and modules including conditioning and characterization, but results from only the seven most-informative series of tests are presented. The seven tests have been placed into two groups based on the test condition imposed upon the batteries during the rest intervals. In the first group, batteries were clamped at a predetermined voltage during the rest intervals (Tests 1 – 4). The second group includes those tests where batteries were allowed to stand (drift) at open circuit conditions during the rest intervals (Tests 5-7). [Note: To expedite testing, the OCV drift due to self-discharge was simulated by a C/25 discharge for 5 hours resulting in a 20% net discharge during that period of time.]

Several other parameters were also evaluated within each test group. The impact of conducting the tests based upon reaching the target voltage (i.e., 30 % depth-of-discharge (DOD) for Tests 1, 3, 5, 6 and 7) from a fully-charged condition compared to reaching the target (i.e., 70% SOC for Tests 2 and 4) from a fully-discharged condition was evaluated. Also, some of the tests included three sets of periodic discharge/charge pulses that enabled calculation of resistances and powers (Tests 1, 2, and 7). Descriptions of the seven tests are summarized in Table 1 and detailed below.

Table 1. NiMH Calendar-Life Test Summary

Test No.	Battery	Rest Condition	Target Condition	Residual Capacity	Periodic Pulses	Loop Test	Comments
1	TOBS	Clamped	30% DOD	55%	yes	1/day	
2	TOBS	Clamped	70 % SOC	70%	yes	1/day	0.9Ah/day charge required.
3	Chinese	Clamped	30% DOD	69%	no	No	
4	Chinese	Clamped	70 % SOC	80%	no	No	
5	Chinese	Simulated OCV	30% DOD	25%	no	20% discharge at C/25 40% recharge at C/1 20% discharge at C/1 to $V_{30\%}$	
6	Chinese	Simulated OCV	30% DOD	45%	no	20% discharge at C/25 30% recharge at C/2 to $V_{80\%}$ 10% discharge at C/1 to $V_{30\%}$	
7	Chinese	Simulated OCV	30% DOD	22%	yes	20% discharge at C/25 30% recharge at C/1 10% discharge at C/1 to $V_{30\%}$	

2.1 Clamped-Voltage Tests

Four variations of the clamped-voltage test were performed on the modules and cells. Parameters varied included the target condition and loop test. The target condition was either 30% DOD or 70%

SOC. Throughout this paper, DOD implies reaching a condition based upon discharging a specified amount of capacity (i.e., Ah) or discharging to a specified voltage, whereas, SOC implies reaching a condition by charging a specified amount of capacity or charging to a specified voltage. The loop tests used during the clamped voltage tests consisted of executing three Hybrid Pulse Power Characterization (HPPC) pulse profiles [2] once per day before or after the rest periods. These pulses were performed at three DOD increments each separated by 10% capacity. This necessitated partially recharging the test article and re-discharging to the target test condition. Hence, the test articles underwent a charge/discharge loop once per day.

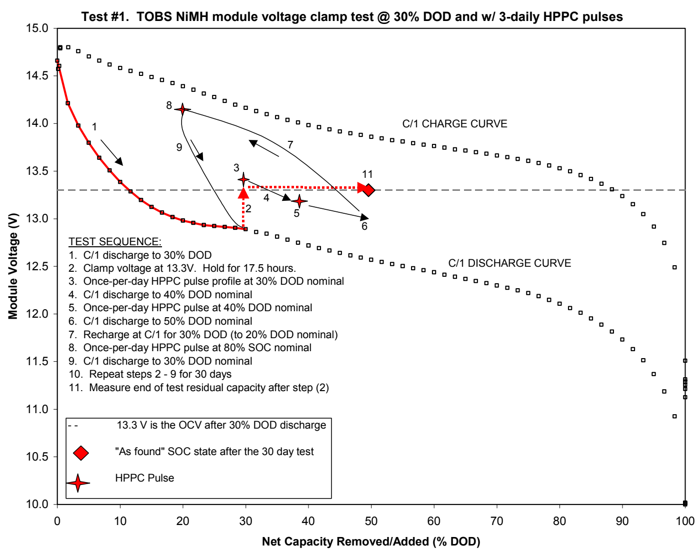


Figure 5. Test Sequence No. 1.

2.1.1 Test Sequence #1

Test Sequence #1 was performed on two TOBS modules. From a fully-charged condition, the modules were C/1 discharged to 30% depth-of-discharge. The modules then sat at OCV for one hour. At the end of the hour, the modules' voltages were clamped at their corresponding OCVs. At the end of the clamp rest period (~17 hours), a series of three HPPC pulses were performed. The first pulse was performed at nominally 30% DOD and the second at 40% DOD, and the third at 80% SOC after applying a C/1 recharge. Following the third pulse, the modules were C/1 discharged to their respective target voltages corresponding to 30% DOD. This sequence was repeated once per day for 30 days. At the end of the 30-day test, the modules' C/1 residual capacities were measured. Figure 5 depicts a stylized version of this test sequence.

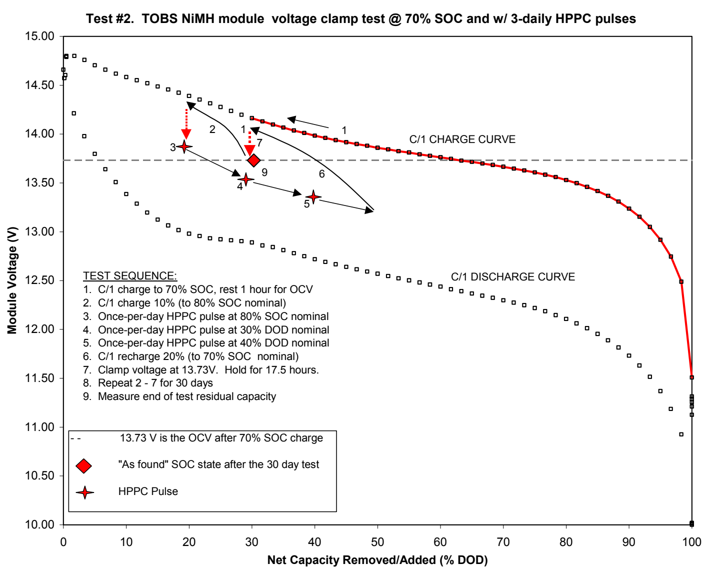


Figure 6. Test Sequence No. 2.

2.1.2 Test Sequence #2

Test Sequence #2 was also performed on two TOBS modules but was SOC-based instead of DOD-based. From a fully-discharged condition, the modules were C/1 charged to 80% SOC. The modules then sat at OCV for one hour after which the three HPPC pulses were applied at 80% SOC, 30% DOD, and 40% DOD, respectively. The modules were then partially C/1 recharged to 70% SOC and then sat at OCV for one hour. At the end of the hour, the modules' voltages were clamped at their corresponding OCVs for the duration of the rest period (~17 hours). Following the rest period, the sequence was repeated once per day for 30 days. At the end of the 30-day test, the modules' C/1 residual capacities were measured. Figure 6 depicts a stylized version of this test sequence.

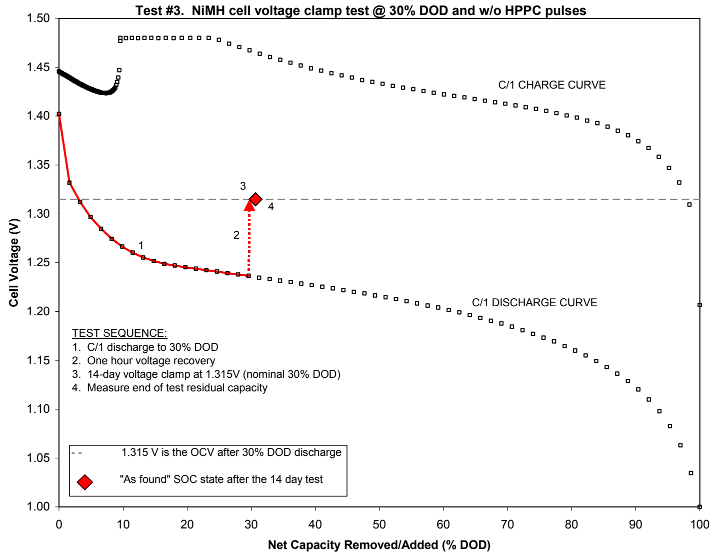


Figure 7. Test Sequence No. 3.

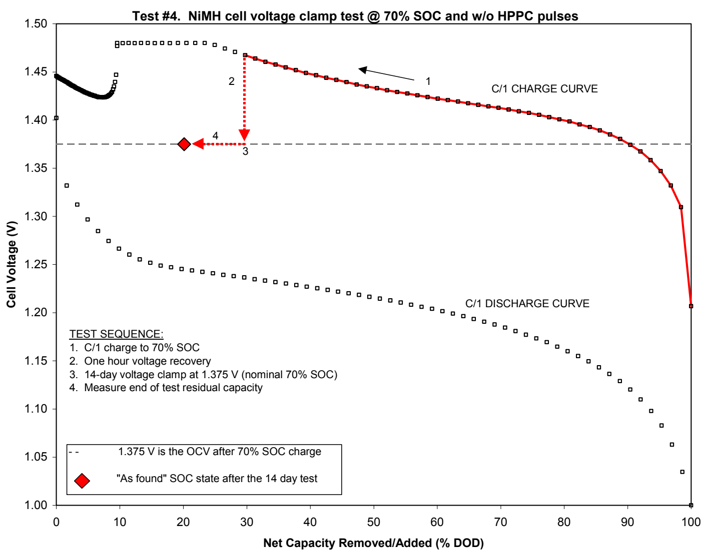


Figure 8. Test Sequence No. 4.

2.1.3 Test Sequence #3

Test Sequence #3 was performed on two small NiMH cells and was DOD-based similar to Test 1 but did not include any loop test. From a fully-charged condition, the cells were C/1 discharged to 30% depth-of-discharge. The cells then sat at OCV for one hour. At the end of the hour, the cells' voltages were clamped at their corresponding OCVs for 14 days. At the end of the 14-day test, the cells' C/1 residual capacities were measured. Figure 7 depicts a stylized version of this test sequence.

2.1.4 Test Sequence #4

Test Sequence #4 was also performed on two small NiMH cells and was SOC-based similar to Test 2 but did not include any loop test. From a fully-discharged condition, the cells were C/1 charged to 70% SOC. The cells then sat at OCV for one hour. At the end of the hour, the cells' voltages were clamped at their corresponding OCVs for 14 days. At the end of the 14-day test, the cells' C/1 residual capacities were measured. Figure 8 depicts a stylized version of this test sequence.

2.2 Simulated OCV Tests

Three variations of the simulated OCV test were performed on 12 small NiMH cells. For all these tests the target OCV was 30% DOD. Because of time constraints, the OCV rest periods were simulated by C/25 discharges for five hours (simulating a 20% self-discharge capacity decrease that would normally take place over a much longer time). Because of this artificially imposed discharge, the cells were required to be partially recharged and then re-discharged to re-attain their target conditions. Thus, these three test sequences all had an imposed charge/discharge test loop. The last of these three tests also had three HPPC pulse profiles superimposed once-per-loop after the C/25 rest periods.

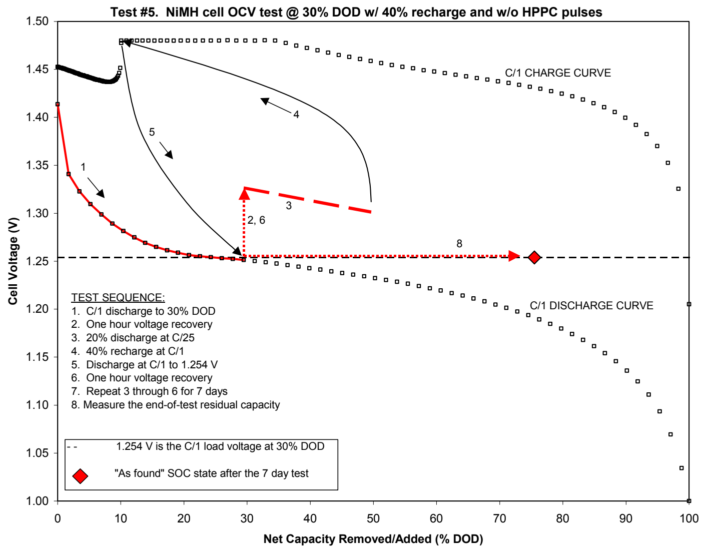


Figure 9. Test Sequence No. 5.

2.2.1 Test Sequence #5

Test Sequence #5 was performed on five small NiMH cells and was DOD-based similar to Test 3 and also did not include any HPPC pulsing. From a fully charged condition, the cells were C/1 discharged to 30% DOD. The cells then sat at OCV for one hour. At the end of the hour, the cells were C/25 discharged for 5 hours to remove a net 20% capacity. The cells were then C/1 recharged to 90% SOC and then C/1 discharged back to a load voltage corresponding to 30% DOD. This loop was applied continuously for 14 days. At the end of the 14-day test, the cells' C/1 residual capacities were measured. Figure 9 depicts a stylized version of this test sequence.

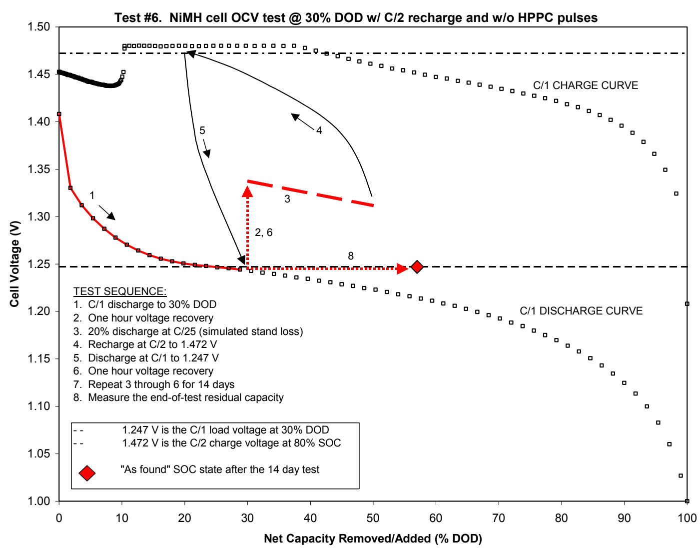


Figure 10. Test Sequence No. 6.

2.2.2 Test Sequence #6

Test Sequence #6 was performed on two small NiMH cells and was DOD-based, also did not include any HPPC pulsing, and was quite similar to Test 5. The only significant differences between Test 5 and Test 6 were the recharge rates during the loop tests and the terminal recharge conditions. From a fully charged condition, the cells were C/1 discharged to 30% DOD. The cells then sat at OCV for one hour. At the end of the hour, the cells were C/25 discharged for 5 hours to remove a net 20% capacity. The cells were then C/2 recharged to a load voltage corresponding to 80% SOC and then C/1 discharged back to a load voltage corresponding to 30% DOD. This loop was applied continuously for 14 days. At the end of the 14-day test, the cells' C/1 residual capacities were measured. Figure 10 depicts a stylized version of this test sequence.

2.2.3 Test Sequence #7

Test Sequence #7 was performed on five small NiMH cells and was DOD-based. It was similar to Test 5 and 6 except for the addition of a series of three HPPC pulses within each test loop. The significant differences between Test 5 and Test 7 were the superposition of the HPPC pulses in Test 7 plus the recharge amounts during the loop test.

From a fully charged condition, the cells were C/1 discharged to 30% DOD. The cells then sat at OCV for one hour. At the end of the hour, the cells were C/25 discharged for 5 hours to remove a net 20% capacity. The cells were then C/1 recharged to 80% SOC and then C/1 discharged back to a load voltage corresponding to 30% DOD. At this point, three HPPC pulses were applied at 30% DOD,

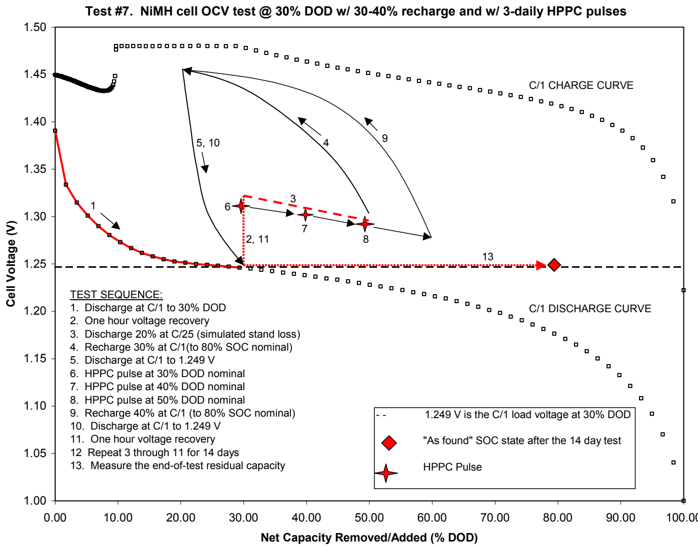


Figure 11. Test Sequence No. 7

40% DOD and 50% DOD, respectively. The cells were C/1 recharged to 80% SOC and then C/1 discharged back to a load voltage corresponding to 30% DOD. This loop was applied continuously for 14 days. At the end of the 14-day test, the cells' C/1 residual capacities were measured. Figure 11 depicts a stylized version of this test sequence.

3. Results

For the clamped-voltage tests involving periodic HPPC pulse profiles, charge balance was based on the combination of a nominally charge-balanced test loop and the voltage clamp itself, which was intended to make up for any minor losses due to coulombic inefficiencies. This intention was realized for Test 2, where no significant shift in SOC occurred over 30 days of testing. However, the amount of charge required to maintain the modules at the clamp voltage was notably larger than could be accounted for by charge/discharge inefficiencies and self-discharge losses. Test 1, starting from a 30% DOD condition, showed a significant SOC shift over the test interval along with much smaller (but inconsistent) charge amounts required to maintain the voltage clamp. These differences suggested that clamping the voltage from a charged (e.g. 70% SOC) condition would be a more effective SOC control mechanism than clamping voltage from a discharged (e.g. 30% DOD) condition. However, they also raised the possibility that battery life could be affected by the large amounts of charge required to maintain the clamp state (about 8% of the battery capacity per day).

Tests 3 and 4 were performed to determine whether these results would repeat if the testing consisted only of clamp voltage intervals without the use of periodic HPPC pulse profiles. In fact SOC drift results during these tests were different from the previous tests: the initial SOC was maintained in the 30% DOD test, while SOC increased during the 70% SOC test. The charge required to maintain the voltage clamp was so small during these tests that firm conclusions cannot be drawn, but the apparent leakage currents for the 30% DOD test were about 1/10 those of the 70% SOC test. The observed charge loss during a 3-day self-discharge test performed on these same cells was intermediate to the values measured in these two tests.

Tests 5, 6 and 7 were performed as possible alternatives for a calendar life test to be done at an open-circuit condition. For such a test, batteries could be in a stored condition for up to a month between periodic reference tests, or indefinitely if full-range reference tests were not performed. During such periods the battery would be expected to self-discharge and to require recharging to maintain an acceptable SOC. For all these tests, the self-discharge was simulated and then the cells were partially recharged. The target SOC was then re-established at a voltage under C/1 discharge load that corresponded to a nominal 30% DOD condition. By recharging the battery above this target condition and then discharging to a consistent voltage, it was hoped that the SOC after repeated iterations would converge to a value near the target SOC.

This did not prove to be the case; the residual capacity in all cases indicated a significant shift in SOC over the test interval of 7 to 14 days. The voltage during the C/1 discharge part of each loop was affected by the preceding recharge step, such that the charge removed to reach this voltage varied significantly from the desired value. This was true whether the recharge step was terminated based on a fixed amount of charge or a fixed terminal voltage. Because Tests 5 and 7 used fixed recharge amounts, the cell SOC tended to iterate downward very quickly, with up to 20% of the cell capacity being lost in the first loop iteration.

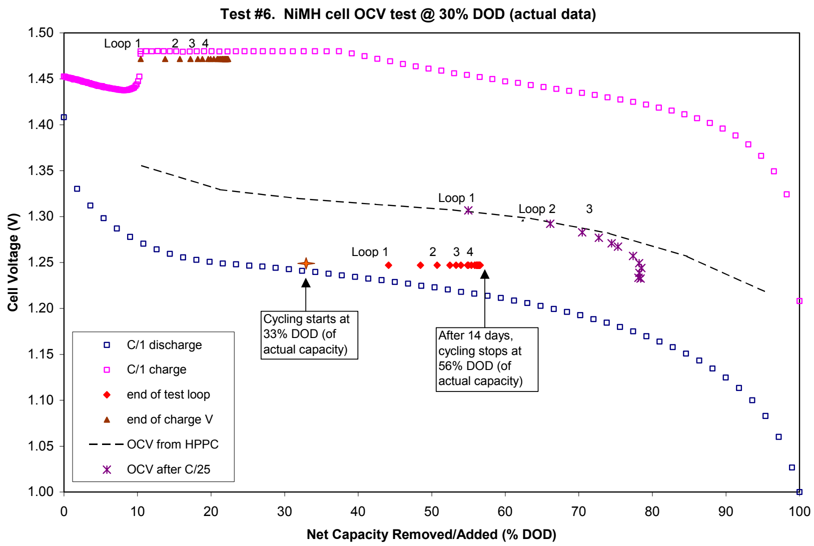


Figure 12. SOC drift behavior in Test No. 6.

Test 6 used a recharge step terminated at a fixed voltage, so the SOC drift was much less severe, but it was still significant. This behavior can be seen more clearly in Figure 12, which shows the calculated SOC values attained during successive iterations of the test loop. It is clear that voltage hysteresis permits a significant variability in both the recharge SOC attained and the subsequent discharge to the target DOD condition.

4. Recommendations and Conclusions

Based on this testing, it was concluded that a calendar life procedure which does not permit either clamping the voltage during storage intervals or periodic full charge and discharge for reference testing is unlikely to be practical for NiMH batteries due to voltage hysteresis effects. Attempts to date have simply not resulted in a test that would give any useful control or monitoring of the battery SOC over an extended test interval. Neither charging/discharging in fixed charge amounts nor to fixed voltage values appears to offer consistent behavior when done indefinitely over less than the battery's full charge range, although some combination of these techniques is likely to be useful over shorter intervals.

The results of this testing are being incorporated in a new FreedomCAR calendar life test procedure still under development. A similar calendar life test being developed for FreedomCAR 42V battery systems is expected to continue to rely on periodic full-scale reference testing with the concomitant restoration of a known charge state.

Further testing is recommended to investigate the observed relationship between NiMH battery leakage current, the clamped/unclamped voltage state of the battery, and the previous charge/discharge history.

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